APPLICATION FOR PATENT

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Title: **A method for automatic color and intensity contrast adjustment of still and video images**

5   **FIELD AND BACKGROUND OF THE INVENTION**

The present invention relates to image processing and, more particularly, to an automatic method for correcting the contrast and intensity of color still and video images.

The perceived colors of visible objects are determined, both by the physics of

10   light reflection and by the way in which the visual system processes the reflected light that it receives. With regard to the physics, the physical color of the light reflected to the visual system by visible objects is determined, both by the reflectivity spectra of their surfaces, and by the color spectrum of the illuminating light. Photographs of scenes, including both still pictures and motion (e.g. video) pictures, whether recorded

15   by analog means (photographic film) or digital means (video cameras), normally are perceived differently from the way the scenes themselves would be perceived by direct vision.

Most prior art methods dealing with color image processing of still and video pictures, and specifically with color and intensity contrast, approach the subject of

20   improving or adjusting such contrast and/or intensity using principles unrelated to the human visual system and its physiology. A previous patent awarded to one of the present co-inventors, U.S. Patent No. 5,771,312, describes physiologically-based color constancy adjustment of pictures, but does not deal with either color or intensity

contrast. We are not aware of any method similar to the one proposed herein, that aims to emulate the human vision for improving color contrast and intensity. Present color contrast adjustment methods thus lack many of the physiological-like features that can lead to much improved color pictures.

5   There is thus a widely recognized need for, and it would be highly advantageous to have, a satisfactory method for performing color contrast correction, either automatically or interactively, on both still and video (motion) pictures. There is also a widely recognized need for, and it would be highly advantageous to have, a satisfactory method for performing local intensity correction, either automatically or

10   interactively, on both still and video pictures.

SUMMARY OF THE INVENTION

The underlying concept of the present invention is to process color pictures in a manner similar to that in which the neurons of the visual system process signals related to color vision to achieve color contrast, and to adjust intensity, which is a

15   component of color.

According to the present invention, there is provided a method for correcting the color contrast of a scene, the scene including an intensity spectrum at each of a plurality of pixels, the method comprising the steps of: a) providing a red image, a green image, and a blue image, each image having a pixel value at each of the

20   plurality of pixels; at each pixel: b) computing a center red response, a center green response and a center blue response based on the images; c) computing a surround red response, a surround green response and a surround yellow response based on the images; d) computing a red, a green and a blue on-center non-filtered and filtered opponent response, based on the center and surround responses; e) computing a red, a

green and a yellow off-center non-filtered and filtered opponent response based on the center and surround responses; f) computing a red, a green and a blue double-opponent (or "do") response and a corresponding filtered do-response based on the on-center and off-center non-filtered and filtered opponent responses; g) computing a

5   red, a green and a blue do-remote signal based on a set of responses selected from the group consisting of the on-center filtered opponent responses and the filtered double-opponent responses; and h) for each pixel: correcting each of the red, green, and blue double-opponent responses for color contrast using respectively the red, green and blue do-remote signals, thereby producing new red, green and blue double-opponent

10   responses.

Preferably, the method for correcting the color contrast of an image further comprises: at each pixel: i)   computing a yellow non-filtered and filtered center response and a non-filtered and filtered blue surround response; j) computing a yellow non-filtered and filtered double-opponent response based on the non-filtered

15   and filtered yellow center and blue surround responses; k) computing a yellow do-remote signal based on a response selected from the group consisting of the filtered yellow center response and the filtered yellow double-opponent response; and l) for each pixel: correcting the yellow double-opponent response for color contrast using the yellow do-remote signal, thereby producing a corrected yellow double-opponent

20   response.

Preferably, the method for correcting the color contrast of an image further comprises: for each still image and for each pixel: a) inversely transforming the red, green and blue corrected double-opponent responses to obtain corresponding new red, green and blue opponent responses; and b) transforming the new red, green and blue

25   opponent responses into corresponding new red, green and blue center responses.

Preferably, the method for correcting the color contrast of an image further comprises: for each picture and for each pixel: a) inversely transforming the corrected yellow double-opponent response to obtain a new yellow opponent response.

The method of color contrast adjustment according to the present invention can also be used to decrease artifacts of image compression (especially JPEG pictures), and to decrease artifacts of both compressed and uncompressed picture transmission

According to the present invention there is further provided a method for adjusting an achromatic contrast of a scene, the scene including an intensity spectrum at each of plurality of pixels, the method comprising the steps of: a) providing an image that has an intensity value at each of the plurality of pixels; at each pixel: b) obtaining an adapted opponent center response using a plurality of the pixel intensity values, and c) at each pixel, correcting the achromatic contrast using the adapted opponent center response.

Preferably, the method for adjusting an achromatic contrast of a scene further comprises obtaining an adapted opponent surround response, wherein the step of correcting for achromatic intensity contrast includes subtracting the adapted opponent surround response from the adapted opponent center response.

According to the present invention there is further provided yet another method for adjusting an achromatic contrast of a scene, the scene including an intensity spectrum at each of a plurality of pixels, the method comprising the steps of: a) providing an image having a pixel value at each of the plurality of pixels; at each pixel: b) computing a center response based on the image; c) computing a surround response based on the image; d) computing a non-filtered and filtered on-center opponent response, based on the center and surround responses; e) computing a non-filtered and filtered off-center opponent response based on the center and surround

responses; f) computing a double-opponent response and corresponding filtered double-opponent response based on the filtered on-center and off-center opponent responses; g) computing a do-remote signal; and h) for each pixel: correcting the double-opponent responses for achromatic contrast using the do-remote signal.

5   The method of achromatic contrast adjustment according to the present invention can be used to decrease artifacts of image compression (especially JPEG), to enhance achromatic contrast in pictures taken under poor lighting conditions or with poor equipment, and to decrease artifacts of both compressed and uncompressed image transmissions. Both color contrast and achromatic contrast adjustments as

10   described herein can be applied to any type of arrayed data (or image), for example to an image represented in polar coordinates, etc.

Implementation of the algorithm (methods) for both color and intensity contrast correction, and also for object recognition, of the present invention may take one or more of this preferred forms:

15   1.   a) Hardware: i. implementation on a dedicated chip; ii. implementation on a dedicated computer slot; iii. integration with another chip; and iv. integration with any other chip computer slot.

b) Software: i. implementation as an add-on software to the hardware devices of 1(a); ii. implementation as a stand-alone software package; and iii. integration with

20   another software package (such as CAD, image processing, etc.).

2.   Enhancement of color contrast and intensity for still and video cameras. Cameras may include digital cameras and miniature video cameras (for video over IP applications).

3.   Enhancement of color contrast and intensity in any imaging application, such

25   as: a) Biomedical – endoscopy, diagnostic imaging (such as CT, MRI, etc). b) Science

and research – any imaging for astronomy, chemistry, physics, biology, computer science, etc. c) Industrial – print industry (including digital-print), inspection, artificial imaging and robotics of any kind, automatic character or object recognition (OCR or ATR). d) Military and security applications – satellite images, long and short distance

5   imaging and surveillance (ground based and aerial), displays, night vision and thermal vision (as false colors). e) Sports, news, fashion, commercials and advertisements. f) Professional, amateur and artistic photography.

4.   Communication: a) Elimination of artifacts in transmitted images (still and video) due to compression (such as JPEG and MPEG) and transmission media affects.

10   Applications may include video conferencing, broadcast, TV (of any format), HDTV.

5.   Software applications: a) Enhancement of color contrast and intensity of images in a privately owned web-site. b) Same as (a), but as a download software. c) Same as (a) as a stand-alone software package. d) Same as (a) as a service (or even as a link) to another web site. End users may come from one or more of the the fields of

15   interest of 3 and 4.

The underlying concept of the present invention is to process color pictures in a manner similar to that in which the neurons of the visual system process signals related to color vision to achieve color contrast. Ideally, the input to the present invention is the intensity spectrum of a scene as a function of wavelength, measured at each pixel in an

20   array of pixels. The term "scene", as used herein, refers to a set of objects that produce, by emission, by scattering or by reflection, visible light that can be perceived by a viewer. For example, a person viewing a pastoral scene sees light reflected by objects in the scene such as trees, grass, rocks and soil, as well as the scattered blue light of the sky. In each of the viewer's eyes, light from the scene is focused by the lens of the eye onto

25   the retina of the eye. The light impinging on each point of the retina is characterized by

an intensity spectrum that spans the full range of wavelengths of visible light. In the case of an imaging apparatus such as a digital camera, the optics of the imaging apparatus typically focuses the light onto an array of sensors such as charge coupled devices; each sensor then produces a set of signals that correspond to spectral subbands of the light

5   from one pixel of the scene. Ideally, the intensity spectrum would be multiplied by the spectral response function of each of the types of photoreceptor cells of the retina (red cones, green cones, and blue cones) to incident light, and integrated with respect to wavelength, thereby providing, at each pixel, a red intensity value, a green intensity value, and a blue intensity value. Collectively, the red values, the green values, and the

10   blue values are examples of what is referred to herein as "images": rectangular arrays of values, one value per pixel. These values then are processed according to the algorithm of the present invention to provide images corrected for color contrast and intensity contrast.

This ideal input rarely is attainable. Therefore, the scope of the present invention

15   includes the processing of images obtained by other means. For example, the three input images may be in the form of analog signals from transducers whose spectral responses are similar to the spectral responses of cone cells, in which case the intensity values are electrical signals, typically voltage levels. These analog signals may be processed directly, using an embodiment of the present invention in analog hardware.

20   Alternatively, these analog signals may be digitized, and processed digitally according to the present invention. Usually, however, the input to the present invention consists of digital images, such as are acquired by video cameras, that come ultimately from transducers whose spectral responses does not necessarily match the responses of cone cells. In that case, the digital pixel intensity values can be transformed to photoreceptor

25   response coordinates, or "fundamentals", corresponding to the spectral responses of the

three types of cones, the responses of similar transducers that are used as "cones", or inputs from any other color scale..

The most common color coordinate system for digital color images is the so-called red-green-blue, RGB, or chromaticity, coordinates. Digital images in other three-

5   color schemes, such as yellow-cyan-magenta, may be transformed mathematically to r-g-b. The transformation from RGB coordinates, or from CIE Yxy coordinates, to photoreceptor coordinates may be found, for example, in G. Wyszecki and W. S. Styles, "Color Science" (Wiley, 1982), pages 139 and 615. In what follows, all references to "red", "green" and "blue" will be to photoreceptor response coordinates, and not to

10   chromaticity coordinates, and instead of the RGB scale, use will be made of the LMS (long-medium-short wavelength) scale. When "red" "green" and "blue" are specified, they are used as equivalents to L, M, and S respectively.

The present invention includes an algorithm in the spirit of that presented by Ronen Dahari and Hedva Spitzer in an article titled "Spatiotemporal adaptation model for

15   retinal ganglion cells", published in the Journal of the Optical Society of America Series A, Volume 13 Number 3 (March 1996), which article is incorporated by reference for all purposes as if fully set forth herein. The paper by Dahari and Spitzer presents a model for the adaptation of visual perception to changing intensity of illumination. It has been conjectured that color contrast perception and intensity contrast perception work by an

20   analogous mechanism, with modifications as described herein.

FIG. 1 is a schematic description of a cross section of the human retina, showing that the retina consists of five layers of cells, primary receptors 4, horizontal cells 6, bipolar cells 8, amacrine cells 10, and retinal ganglion cells 12. Receptors 4 shown here are cone and rod cells together. The rods respond to light intensity, rather

25   than color. The mechanism of adaptation to changing intensity modeled by Dahari and

Spitzer operates in achromatic retinal ganglion cells **12**. The RF of both chromatic and achromatic ganglion cells **12** includes both on-center and off-center receptors **14** of the center RF area, and receptors **16** of the surround RF area. Hereafter, "center" and "surround" may be written as "cen" and "srnd" respectively.

5   The responses of center area sub-regions **14** and surround area sub-regions **16** are combined in ganglion cell **12**, in one of two different ways, depending on the type of ganglion cell **12**. As shown in FIG. 2, an "on-center" cell **20** responds positively ("+") to signals of increased light intensity **24** (e.g. L^+) from the center area (or sub-region) of the RF, and negatively to signals of increased light intensity **26** (e.g. M^-)

10   from the surround area (or sub-region) of the RF. An "off-center" cell **22** responds negatively ("-") to signals of increased light intensity **28** from the center area of the RF (e.g. L^-), and positively to signals of increased light intensity **30** from the surround area of the RF (e.g. M^+). Cells **20** and **22** are also referred to as "opponent" cells. The physiological responses can be translated into mathematical expressions, and this will

15   be done consistently throughout the following description.

The "double-opponent" cells of the visual cortex (which have spatially larger RFs than the opponent cells), combine the responses of the on-center and off-center retinal ganglion (opponent) cells in a manner that resembles a mathematical spectral and spatial derivative. For example, FIG. 3 shows a double-opponent cell **40** that gets

20   its own double-opponent center response L_{do-c} ("double-opponent center" response, or "do-center" response) from a first group of on-center ganglion cells **42** (for example, L^+M^-, the group that subtracts green surround responses from red center responses) whose RFs are located in a do-center area **44**, and gets its own double-opponent surround response L_{do-s} ("do-surround response") from a corresponding group of off-

center (e.g. L^-M^+) cells **46**, whose RFs are located in a do-surround area **48**. The do-surround response is related to area **48**.

A "do-remote" area **50** has the shape of an annulus, concentric with that of the "do-center" and of the "do-surround" areas. Typically, the internal diameter of the

5   "do-remote" area is equal to the external diameter of the "do-surround" and therefore does not overlap the "do-center" or the "do-surround"s. However, there may also be some overlap or some gaps between the do-remote and the do-surround areas

One of the innovative aspects of the present invention is, that in contrast with US pat. 5,771,312, in the color contrast adaptation of the present invention the

10   influence of a "remote" region affects the color contrast response of double-opponent (cortical) cells.

There are six (or alternatively eight, including the yellow on- and off-center cells) main groups of retinal ganglion cells **12** involved in color perception, corresponding to the three kinds of cone cells that respond to color analogously to the

15   response of receptors (rod cells) **4** to intensity. An image is first processed in three most common color-coded channels in the retina (L^+M^-, M^+L^- and $S^+(L+M)^-$) to three activation-level maps of on-center opponent P-LMS cells through different retinal layers originating in (receptors) cones **4** (FIG. 1). The off-center opponent cell types L^-M^+, M^-L^+ and $S^-(L+M)^+$ have similar RF structure but with opposite signs. The

20   input to the cones level is the spectral composition of the light reaching the retina, when illumination falls on a surface of the objects and is reflected from it. The field of view is mapped by the three types of cones, L, M and S. The quantum catches of the three cone types, $L_{pigment}$, $M_{pigment}$ and $S_{pigment}$, are typically expressed by an integration of the inner triple product of the spectral sensitivity of each pigment type

with the reflectance properties and with the spectral and intensity absorption properties of the surface, at any specific location in the image (Wyszeki & Styles). The responses of the three cone-types, L_{cone}, M_{cone} and S_{cone}, normalized separately to a range of 0-1, are typically expressed by a Naka-Rushton equation as a function of

5   their inputs $L_{pigment}$, $M_{pigment}$ and $S_{pigment}$ (Dahari and Spitzer; Wyszeki & Styles). The input red, green, and blue intensity values are treated as though they are the responses of red, green and blue cone cells.

The intensity values are transformed into a "response image" in a manner similar to that by which on-center and off-center retinal ganglion cell respond to

10   inputs from cone cells and other cells in the retinal pathway. It is to be understood that in the present invention, in a manner analogous with that of US. Pat. 5,771,312, references to an "image" herein are references to values at pixels, or "pixel values", treated collectively as an array. Thus, the term "image" as used herein includes purely mathematical objects, and does not necessarily correspond to a physical image,

15   although the original input images certainly do correspond to physical images.

The first stage of the forward transformation is performed analogously to the top path of FIG. 1 of Dahari and Spitzer (notwistanding the fact that Dahari and Spitzer's paper does not contain color information), to provide, at each pixel, an opponent red center response (the pixel value of a "response function"), an opponent

20   green center response, and an opponent blue center response. Optionally, a fourth, yellow opponent center response, which is calculated by simply adding the red and green responses, is obtained with the same forward transformation. In what follows, the fourth color (yellow) is optional in all transformations at the level of opponent and double-opponent cells. A similar transformation is used to obtain red, green and blue

25   surround responses. These surround responses are subtracted from the center

responses, in emulation of the action of "on-center" and "off-center" retinal ganglion cells, as follows: the green surround response is subtracted from the red center response; the red surround response is subtracted from the green center response; and the red surround response and the green surround response are averaged to form a

5   yellow surround response, which is subtracted from the blue center response. Optionally, the blue surround response is subtracted from the yellow center response.

The second stage of the forward transformation deals with the simulation of double-opponent responses that emulate the action of (cortical) "double-opponent" color coded P_{do}-LMSs cells, and includes an additional remote adaptation. The color-

10   coded double-opponent cells are adapted (corrected) by a remote adaptation in a manner similar to a mechanism based on psychophysical findings, as shown in Singer & D'Zmura, Vision Research, vol. 34, pp. 3111-3126, 1994. Adaptation is also explained (but not in relation to color and do-remote area) in Dahari and Spitzer. Note that "remote" adaptation refers to the effect of regions peripheral to the "classical"

15   RF.

The third stage deals with the simulation of an "inverse" transformation", i.e. the transformation of the activity of these double-opponent "adapted" cells to a perceived image in a standard CIE notation (XYZ), in a RGB scale, in a Lu*v* scale, or in any other standard color scale.

20   Regarding intensity contrast adjustment, the method includes similar forward and, optionally, inverse transformations, carried out by the emulation of the action of magno (M) cells.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is herein described, by way of example only, with reference to the

accompanying drawings, wherein:

FIG. 1 is a schematic cross section of a human retina;

5   FIG. 2 is a schematic description of on-center and off-center opponent receptive

fields;

FIG. 3 is a schematic description of a double-opponent RF having a corresponding

double-opponent remote sub-region;

FIG. 4 is a schematic illustration of the operation performed to obtain a filtered

10   opponent response.

FIG. 5 is a schematic description of a double-opponent receptive field that includes the

remote influences.

FIG. 6 is an alternative schematic description of a double-opponent receptive field that

includes the remote influences.

15   **DESCRIPTION OF THE PREFERRED EMBODIMENTS**

The mathematical simulation of the physiological processes related to color

contrast perception proceeds as follows: the spatial response profiles of the two sub-

regions of each (on- and off-) ganglion cell RF (P-RGC), the "center" and the

"surround" regions, are preferably expressed by a Difference of Gaussians (DOG). As

20   in Dahari and Spitzer, the first step of the present invention is the transformation of each

input image to an "output function" or "spectral response function" G. For each color

(red, green and blue), there is a center spectral response function G_c (also written as L_{cen},

M_{cen} and S_{cen}) and a surround spectral response function G_s (also written as L_{smd}, M_{smd}

and S_{smd}). Each of the three center response functions G_c is computed by convolving the

25   corresponding color image with a center local spatial Gaussian filter f_c, as shown in

equations 2 and 3 of Dahari and Spitzer, thereby producing a center smoothed image whose pixel values are the required G_c's. Similarly, each of the three surround response functions G_s is computed by convolving the corresponding color image with an opposite sign surround local spatial Gaussian filter f_s, thereby producing a surround smoothed

5   image whose pixel values are the required G_s's. Typical values of the radii ρ of the Gaussian filters are 0.5 pixels for the center filter and 0.5-9 pixels for the surround filter.

Optionally, the pixel values may be saturated before the spatial filtering with the Gaussian filters:

$$p := p/(p + p_0)$$

10   wherein p represents a pixel value, p_0 is a saturation constant, and ":=" represents replacement.

An emulated opponent response R_{op} (where R refers to L, M, S and optionally Y="yellow") is the subtraction between the center and the surround response values at a given pixel: for on-center cells the opponent response is expressed as L^+M^-, M^+L^-

15   and $S^+(L+M)^-$, and for off-center cells as L^-M^+, M^-L^+ and $S^-(L+M)^+$ Opponent responses are calculated next. Specifically, for "on-center" opponent responses

$$R_{op\,(l+)} = L^+M^- = G_{c,l} - G_{s,m} \qquad (1)$$

$$R_{op\,(m+)} = M^+L^- = G_{c,m} - G_{s,l}$$

$$R_{op\,(s+)} = S^+(L+M) = G_{c,s} - (G_s + G_{s,})_{(l+m)}/2$$

20   Optionally, a yellow center response ($R_{op((m+l)+)}$) is also used. Similar subtractions are carried out to obtain "off-center" opponent responses L^-M^+, M^-L^+ and $S^-(L+M)^+$ (and optionally a yellow opponent response $R_{op((m+l)-)}$) by subtracting the blue surround response from the yellow center response.

The action of the RFs of double-opponent cells is emulated in one of two

25   ways: 1) by assigning the emulated filtered response (explained below) (or response

in the specific case of feeding one opponent cell as the center of double opponent center receptive field region) of a first on-center opponent group (for example L^+M^-) to a "do-center" response, and assigning the emulated filtered response of a corresponding, off-center opponent group (for example L^-M^+) to a "do-surround" response, or 2) by using emulated filtered responses of "on-center" type opponent groups (or response in the specific case of feeding one opponent cell as the center of double opponent center receptive field region), for

example assigning the emulated filtered response of an on-center L^+M^- group to a do-center response, and the emulated filtered response of an on-center M^+L^- group to a do-surround response. Hereinbelow, the "-" sign in all subscripts including two or more letters, for example in "do-c" of $L_{do\text{-}c}$, means "of" e.g., "$L_{do\text{-}c}$= *the red response of the double-opponent center*". An exemplary mathematical formulation for the three-color double-opponent center responses is given by:

$$L_{(do-c)} = \iint\limits_{center\ area} R^*_{op(l+)} f_{(c-do)}(x,y)\,dxdy$$

$$M_{(do-c)} = \iint\limits_{center\ area} R^*_{op(m+)} f_{(c-do)}(x,y)\,dxdy \qquad (2)$$

$$S_{(do-c)} = \iint\limits_{center\ area} R^*_{op(s+)} f_{(c-do)}(x,y)\,dxdy$$

$R^*_{op\ (l+)}$, $R^*_{op\ (m+)}$, $R^*_{op\ (s+)}$ (and optionally a fourth "yellow" $R^*_{op((l+m)+)}$) are each both a spatial and a spectral filtered response, similar to $R_{op\ (l+)}$, $R_{op\ (m+)}$, $R_{op(s+)}$ (and optionally the fourth "yellow" $R_{op((l+m)+)}$) but related to different areas than the corresponding R_{op}s. R_{op} and R^*_{op} and similar pairs below are also referred to herein as, respectively, "non-filtered" and "filtered" responses (in spite of the fact that the "non-filtered" values are obtained of course with operations involving filters). The relationship between non-filtered and filtered opponent responses is illustrated

schematically in FIG. 4, where an examplary (non-filtered) on-center opponent response $R_{op}(x_1,y_1)$ is calculated for pixel **62** centered at (x_1,y_1) using eq. 1, i.e. subtracting the value at (x_1,y_1) of a surround response function $G_s(x_1,y_1)$ from a center response function $G_c(x_1,y_1)$. As explained above, both $G_s(x_1,y_1)$ and $G_c(x_1,y_1)$ are

5   functions obtained by convolutions involving local filters. A filtered response $R_{op}*(x_1,y_1)$ to be used in eq. 2 for the computation of the do-center responses for the do-cell centered at (x_1,y_1), (and thus associated with $R_{op}(x_1,y_1)$) is calculated in general by applying the local filters in the convolutions yielding G_c and G_s at <u>different</u> (than x_1,y_1) locations **62**. The "filtering" operation for obtaining filtered responses

10   thus involves moving the filters over the relevant area of the integration and obtaining for each pixel a function value. The value of $R*_{op}$ is in general different from that of R_{op}, except for the special case when both are calculated at the same (x,y).

Optionally, a fourth yellow do-center response is obtained as $((M+L)-S)_{d+cen}$ by using $R*_{op((l+m)+}$. Thus, the responses $L_{(do-c)}$, $M_{(do-c)}$ and $S_{(do-c)}$ (and optionally

15   $(M+L)-S)_{d+cen}$) are the products of convolutions of corresponding filtered opponent responses with a center spatial weight function $f_{(c-do)}$. $f_{(c-do)}$ is preferably a radially symmetric Gaussian exponentially decaying function, with a radius of 1-6 pixels.

The do-surround responses are computed in a similar fashion. An exemplary mathematical formulation for the three color double-opponent surround responses

20   (and optionally a fourth, yellow $(L+M)_{(do-s)}$) is given by:

$$L_{(do-s)} = \iint_{surround area} R*_{op(l-)} f_{((s-do)}(x,y)dxdy \qquad (3)$$

$$M_{(do-s)} = \iint_{surround area} R*_{op(m-)} f_{(s-do)}(x,y)dxdy$$

$$S_{(do-s)} = \iint_{surround area} R*_{op(s-)} f_{(s-do)}(x,y)dxdy$$

where $R^*_{op(l-)}$, $R_{op}^*{}_{(m-)}$, and $R_{op}^*{}_{(s-)}$ (and optionally a fourth "yellow" $R^*_{op((l+m)-)}$) are

off-center filtered responses similar to $R_{op\ (l-)}$, $R_{op\ (m-)}$, $R_{op(s-)}$ (and optionally $R_{op((l+m)-)}$)

but related to different areas, as explained above. These off-center filtered opponent

responses are convolved with a surround spatial weight function $f_{(s-do)}$. $f_{(s-do)}$ is

5   preferably an radially symmetric Gaussian exponentially decaying function with a

radius of 9-31 pixels.

As mentioned above, a key innovative element of the present invention is the

addition of a new, "do-remote" signal needed for the adaptation mechanism of color

contrast, for each double-opponent cell. This "do-remote" signal represents the

10   peripheral area that extends far beyond the borders of the classical RF of the P_{do}-LMS

double-opponent cell. The four do-remote signals ($L_{(do-remote)}$, $M_{(do-remote)}$, $S_{(do-remote)}$

and $(L+M)_{(do-remote)}$ that emulate the effect of the remote areas of the double-opponent

cells are defined in eq. 4 as the convolution of a corresponding filtered double-

opponent center response with a remote spatial weight function (representing spectral

15   content) f_r applied to do-remote area **50**, for each pixel in the remote area.

$$L_{(do-remote)} = \iint_{remote-area} L^*_{(do-c)}\ f_r(x,y)dxdy \qquad (4)$$

$$M_{(do-remote)} = \iint_{remote-area} M^*_{(do-c)}\ f_r(x,y)^{\rightarrow}\ dxdy$$

$$S_{(do-remote)} = \iint_{remote-area} S^*_{(do-c)}\ f_r(x,y)dxdy$$

$$Y_{(do-remote)} = (L+M)_{(do-remote)} = \iint_{remote-area} \frac{(L+M)^*{}_{(do-c)}}{2} f_r(x,y)dxdy$$

where $L^*_{(do-c)}$, $M^*{}_{(do-c)}$, $S^*{}_{(do-c)}$, and $(L+M)^*_{(do-c)} = Y^*{}_{(do-c)}$ are double-opponent

center filtered responses acting on the do-remote areas, related to the responses of eq.

2 in the same fashion as explained above for opponent responses. In other words, the

same calculations that were carried out for opponent RFs are done here, but in relation to each pixel that belongs to the do-remote area.

f_r is preferably an exponentially decaying spatial-weight function, an example of which is shown in Eq. 5. Alternatively, f_r can be a Gaussian function, or any other

5   decaying function.

$$f_r(x, y) = \frac{\exp\left[-\sqrt{(x^2 + y^2)}\Big/ K_{remote}\right]}{A_{remote}} \tag{5}$$

K_{remote} is a constant which defines the slope of the weight function, and A_{remote} is a factor of normalization to a unit:

$$A_{remote} = \left(\iint\limits_{remote-area} \exp\left(-\frac{\sqrt{x^2 + y^2}}{k_{remote}}\right)\right) \tag{6}$$

The next step is obtaining the responses of the double-opponent RFs that are fed by

10   both the do-center responses (eq. 2) and by the do-surround responses (eq. 3). The double-opponent responses or "output functions", before the adaptation stage are given by:

$$L_{do} = L_{(do - c)} - M_{(do - s)} \tag{7}$$
$$M_{do} = M_{(do - c)} - L_{(do - s)}$$
$$S_{do} = S_{(do - c)} - (L + M)_{(do - s)}$$

Optionally, a fourth (yellow) double-opponent output function is obtained by subtracting the blue do-surround response from the yellow do-center response. The

15   do-remote signals of eq. 4 can alternatively be built from filtered double-opponent responses $L^*_{(do)}$, $M^*_{(do)}$, $S^*_{(do)}$ and $Y^*_{(do)} = (L+M)^*_{(do)}$ (related to the do-responses in

eq. 7 as explained for the opponent case above) through appropriate convolutions with the remote spatial weight function, instead of using the double-opponent center filtered responses $L^*_{(do-c)}$, $M^*_{(do-c)}$, $S^*_{(do-c)}$ and $Y^*_{(do-c)}$.

5   As can be understood from the subscripts "c" (center), "s" (surround), "do-c" (double-opponent center), "do-s" (double-opponent surround) and "do-r" or "do-remote" (double-opponent remote), the various receptive fields ("RF") and spatial convolutions extend over different numbers of pixels. FIGS. 5 and 6 show two different schematic descriptions of double-opponent RFs which include the remote influences. FIG. 5 shows an on-center cell **100** with a center RF **102** (pixel **A**) and a surround RF **104** (pixels **B**).

10   The on-center cell is surrounded by 9 off-center cells **106**, each with a center RF **108** (pixel **C**) and a surround RF **110** (pixels **D**). Cell **100** and cells **106** are "opponent cells", and together constitute a double-opponent ("do") cell **112**, on-center cell **100** constituting a "do-center" RF, and off-center cells **106** constituting a "do-surround" RF. Do-cell **112** has a do-remote RF **114**, which includes on-center opponent cell RFs **116**, each with a

15   center RF **118** (pixel **E**) and a surround RF **120** (pixels **F**). For simplification purposes, only nine such RF **116** are shown in the upper right corner of do-remote RF **114**, with the understanding that they are repeated in the rest of the (unmarked) pixels. The different marking of pixels in cell **100** and RFs **116** indicates the different values resulting from the application of different spatial weight functions at those locations. In

20   the example of FIG. 5, the different receptive fields extend over different areas: for both on-center and off-center opponent cells, the center RF includes one pixel, while the surround RF extends over the 8 pixels immediately surrounding each center. For double-opponent cell **112**, do-center RF **100** extends over 9 pixels and the do-surround RF (which includes the nine cells **106**) extends over the adjacent 72 pixels. Do-remote RF

25   **114** extends over the 648 pixels surrounding do-cell **112**. It should be clear that the

different areas over which the spatial weight functions are applied in the convolutions can also partially overlap, or be separated by gaps. For example, cells **106** whose RFs compose the do-remote RF and who are used in computing the do-remote signal can partially overlap, or can be separated by gaps.

5   FIG. 6 shows an alternative double-opponent RF description. The main difference vs. FIG. 5 lies in the composition of the do-remote RF: instead of (as in FIG. 5) being composed entirely of on-center cell RFs, a do-remote RF **130** is composed here of a group of do-cell RFs **132**, each RF **132** composed of a center "on-center" opponent RF **140** (pixels **E** and **F**) and nine surrounding "off-center" opponent RFs **142** (pixels **G**

10   and **H**). For simplification purposes, only one of the nine RF **132** is shown in detail. The pixels in the on-center and off-center RFs of the do-center, surround and remote regions are again marked differently to indicate the effect of the convolutions with different spatial weight functions. The do-remote area extends over the same number of pixels as in FIG. 5

15   The descriptions in FIGS. 5 and 6 are for illustration purposes, and the areas given are typical. However, it is to be understood that each area mentioned can extend over a range around the typical value cited. Thus, an opponent surround RF (e.g. **104**) may include the 16 pixels immediately surrounding the eight pixels mentioned above, thereby extending over a total of 24 pixels. The RF of a double-opponent center typically

20   extends over about 3 by 3 pixels, see FIG. 6. The do-surround RF may extend over an area defined by another 11 pixels extending each way in both x and y (i.e. bound externally by a boundary of 31x31 pixels) while the do-remote RF may extend an additional 10 pixels in each direction (i.e. bound externally by a boundary of 51x51 pixels, and internally by the 9x9 to 31x31 boundary). The domains of the convolutions

for computing the different terms roughly overlaps the corresponding RF areas. At the boundaries of the images, all convolutions use periodic boundary conditions.

Adaptation

5   The adaptation for color contrast correction is carried out on the double-opponent responses of eq. 7, in a manner analogous to the adaptation procedure in Dahari and Spitzer, by using the do-remote signals. In the form of the present invention that is applied to digital video photography, time variation is taken into account. The output functions G (where G stands for L_{do}, M_{do} and S_{do}, the double-opponent output

10   functions in eq. 7) are now functions of time t, specifically the sampling time of the images. In addition to the spatial and spectral weight functions which are applied above to entire images at a single value of t, temporal filters, as defined below, are applied pixel-wise to these functions of t. Two kinds of temporal filters are used: temporal, preferably low pass filters, which are independent of the functions to which

15   they are applied, and adaptive temporal filters, which depend, at any given time t, on the prior history of the functions to which they are applied.

For each color, the present invention computes an adapted (or "corrected") double-opponent response $R_{(do-a)}(G,t)$ at each pixel by using a Naka-Rushton-like equation:

$$R_{(do-a)}(G,t) = R_{max} \frac{G(t)}{G(t) + \sigma(G,t)} \tag{8}$$

20   R_{max} is a maximum response that is used as a normalization factor. For the remote adaptation of each double-opponent RF region, an adaptive function $G_b(t)$ analogous to Dahari and Spitzer's adapting component $G_b(t)$, is used in the computation of the semisaturation term σ,:

$$\sigma(t) = \alpha G_b(t) + \beta \qquad (9)$$

In the application of the method to still photography (no time dependence) i.e. at steady state (at $t=\infty$), function G_b is time-independent and is given (using the red double-opponent response as an example) by:

$$G_{b(t=\infty)} = L_{(do\text{-}remote)} \qquad (10)$$

5   Similar equations are used for the other colors response components (green, blue and optionally yellow). Unlike Dahari and Spitzer, the Naka-Rushton equation of the present invention is applied to the *double-opponent* RFs (emulating the cortical color-coded cells), and the adaptation factor (the "remote influence") is applied to the semi-saturation term in the denominator of eq. 8. More generally, for example in video

10   applications, the adaptive function is computed by convolving the corresponding output function with corresponding adaptive temporal filters as shown in equations 7 and 8 of Dahari and Spitzer, and in the boxes labeled "dynamical adaptive filter" of FIG. 1 of Dahari and Spitzer. The temporal filters are applied pixel-wise and locally to the entire image. What makes these filters adaptive is that the associated time "constants" actually

15   are functions of both time and the prior history of G. The most preferred form of the function τ_b that describes the decay of the adaptive filter is:

$$\tau_b(t) = \tau_m/(\ 1 + abs(\ G(t) - G_b(t)\ )/G_n\ ) \qquad (11)$$

In this expression, τ_m is the maximum expected value of $\tau_b(t)$, $G(t)$ is the output function, after convolution with the corresponding low-pass temporal filter; $G_b(t)$ is the adaptive

20   function, i.e., the output of the convolution, at times prior to the time at which the convolution presently is being computed; and G_n is a normalization constant. Because the adaptive filter is causal, it is well-defined despite being defined in terms of its own output.

The change in a gain control effect is achieved by the curve-shifting mechanism of the "response vs. log chromatic (or achromatic) contrast illumination" curve, similar to the "response vs. illumination" curve shown schematically in FIG. 6 in Shapley & Enroth-Cugell, Progress in Retinal Research, vol. 3, pp. 263-346, 1984.

5   The gain control effect of the present invention can be seen as a "second order" effect, in contrast with the first order effect embodied in FIG. 6 of Shapley and Enroth-Cugell. The adaptation is reflected in a shift of the response curve as a function of time. Consequently, each time a new range of input intensities to a color channel is viewed, given that the change from the previous stimulation is sufficiently large, the

10   curve shifts, bringing the system to a new adaptation state. This curve shift takes place according to the temporal filter, causing an apparent decaying function of the response.

The significance of applying a variable dynamic temporal component, aside from corresponding to known physiological phenomena (e.g. as explained in Dahari and Spitzer and the references therein) becomes evident when observing the

15   dynamical color contrast adjustment algorithm performance in the absence of such a component. In such a dynamical case, the rate of adaptation changes as a function of signal magnitude of each contrast channel.

One immediate result of the dynamical properties of adaptation mechanisms in

20   video applications, (as also explained in U.S Pat. No. 5,771,312) is that when a constant image is viewed over a certain time period, its color contrast appears to decay with time.

"Inverse transformation" or transformation of the P_{do-a} LMSs activity to a perceived image

In order to perform contrast on real images it is necessary to inversely transform the adapted (corrected) double-opponent responses (at any location in the image) into a perceived color. Several different inverse functions, based on different assumptions, can be used for this purpose in preferred embodiments of the present invention. The calculated perceived color contrast is the color contrast that would stimulate the triplet of P_{do-a} LMS cells to the same responses, with a uniform non-contrast surface present in their "remote" areas. The rationale that has lead to this definition is the assumption that the visual system interprets color contrast of an object in a way similar to the one described above. The following equations describe the emulation of the three main double-opponent and opponent color-coded cells, but alternatively all these equations can be applied also to the yellow double-opponent and opponent RFs. In general, the steps in the inverse transformation preferably include: using the adapted double-opponent responses to calculate a new value of a double-opponent response ("new do-response"), assigning the new value to the double-opponent center ("new do-center response") thus obtaining a new value of an opponent response ("new opponent response"), and assigning this new opponent response value to get a new opponent center response, thus returning to eq. 1, which now has "new center" values.

A key assumption in performing an inverse function as described above is that the contrast in the "do-remote" area is equal to that in the double-opponent area. This is expressed as

$$L_{do-a} = L_{do-remote} \qquad M_{do-a} = M_{do-remote} \qquad S_{do-a} = S_{do-remote} \tag{12}$$

Inserting for each color the do-remote expressions of eq. 4, and rewriting eq. 8

for each color channel under assumption (12) yields:

$$L_{do-a} = \frac{L_{do}}{L_{do} + \iint\limits_{remote} L*_{do-c} \, f_r(x,y)dxdy}$$ (13)

$$M_{do-a} = \frac{M_{do}}{M_{do} + \iint\limits_{remote} M*_{do-c} \, f_r(x,y)dxdy}$$

$$S_{do-a} = \frac{S_{do}}{S_{do} + \iint\limits_{remote} S*_{do-c} \, f_r(x,y)dxdy}$$

By assuming for each color channel that the semisaturation term expressed by

5   the integral in the denominator equals approximately the adapted double-opponent

response (e.g. as an alternative for the red $L_{do-a} \approx \iint L*_{do-c} f_r(x,y)dxdy$) we get

$$L_{do}' = \frac{(L_{do-a})^2}{1 - L_{do-a}}$$ (14)

$$M_{do}' = \frac{(M_{do-a})^2}{1 - M_{do-a}}$$

$$S_{do}' = \frac{(S_{do-a})^2}{1 - S_{do-a}}$$

where L_{do}', M_{do}' and S_{do}' (and optionally Y_{do}') are the new double-opponent responses.

L_{do}', M_{do}' and S_{do}' (and optionally Y_{do}') are now applied to the corresponding double-

opponent center color channel, i.e., $L'_{do} = L'_{do-c}$, $M'_{do} = M'_{do-c}$, $S'_{do} = S'_{do-c}$, (and

10   optionally $Y'_{do} = Y'_{do-c}$), at each pixel, creating for each color a difference ("change")

between the original double-opponent center response (L_{do-c}, M_{do-c}, S_{do-c}, eq. 2) and

the new do-center response (L'_{do-c}, M'_{do-c}, S'_{do-c})

$$\Delta L_{do-c}(x,y) = L_{do-c}{}'(x,y) - L_{do-c}(x,y) = \frac{L_{do}{}' - L_{do}}{f_{c-do}(x,y) \iint\limits_{cen} dxdy} \quad (15)$$

$$\Delta M_{do-c}(x,y) = M_{do-c}{}'(x,y) - S_{do-c}(x,y) = \frac{M_{do}{}' - M_{do}}{f_{c-do}(x,y) \iint\limits_{cen} dxdy}$$

$$\Delta S_{do-c}(x,y) = S_{do-c}{}'(x,y) - S_{do-c}(x,y) = \frac{S_{do}{}' - S_{do}}{f_{c-do}(x,y) \iint\limits_{cen} dxdy}$$

Remembering that do-center responses are equivalent to opponent responses (connected by a convolution with a weight function) the new do-center response values are equivalent to new opponent response values, in the special case when the do-center RF equals the RF of one opponent cell.

5   In order to find the new opponent center responses, i.e. the new responses of the cones, the ΔL(do-c), ΔM(do-c), and ΔS(do-c) differences are applied to the opponent center, preferably using the following expressions:

$$L'_{cen}(x,y) = a\Delta L_{(do-c)}(x,y) + bL_{cen}(x,y) + cM(x,y)_{srnd} \quad (16)$$

$$M'_{cen}(x,y) = a\Delta M_{(do-c)}(x,y) + bM_{cen}(x,y) + cL(x,y)_{srnd}$$

$$S'_{cen}(x,y) = a\Delta S_{(do-c)}(x,y) + bS_{cen}(x,y) + c(L+M)(x,y)_{srnd}$$

where a ,b and c are constant parameters that can be identical for all color channels, or

10   alternatively are different for each color of the center sub-region. Typical ranges for a, b, and c are a=1-2, b= 0-1 and c=0-2. The outputs of eq. 16, L'_{cen}, M'_{cen}, and S'_{cen} are the new values of L, M and S. Alternatively, the new cone response values can be obtained with a multiplication operation instead of a summation operation, for

example using the following type of expression (for the red channel, with similar expressions for the other color channels): $L'_{cen}(x,y)= aL_{cen}(bL'_{do-c}(x,y) + cL_{cen}(x,y) +dM_{srnd} + \varepsilon)$ where a, b, c, and ε are constant parameters with typical value ranges of: a=1-5; b=1-5; c=0-2, d=0-5, and ε, a constant which is normally 0. For specific uses

5   such as correcting JPEG images, "a" in eq. 16 and in the multiplication operation above can be assigned negative values (e.g. -1 to -5). Thus, modified new cone responses can be obtained either by an additive operation, i.e. by adding a change to the original value, or by a multiplication operation as shown above. Another alternative for obtaining the new opponent center (i.e.cone) responses through an

10   additive operation as in   equation 16   is (for the red channel as an example) $L'_{cen}(x,y)= bL'_{do-c}(x,y) + cL_{cen}(x,y) +dM_{srnd} + \varepsilon$,   where   the typical value ranges are: b=1-30, c=0-1, d=0-5, and ε= normally zero. For specific uses such as correcting JPEG images, "b" in the additive operation above can be assigned negative values (e.g. -1 to -30).

15   Finally, a simple inverse transformation from the LMS scale to the CIE-RGB (either directly or by going through the CIE-XYZ scale) can be performed. It is important to note that the method of the present invention is independent of the color scale used, and that there are other scales, such as the non-linear Lab scale, to which the method of the present invention is equally applicable.

20

Intensity Adaptation

Intensity adaptation or contrast adjustment on the achromatic information in a color image is connected to the color contrast adaptation described above, in the sense that it uses a similar physiological basis for the algorithm and a similar sequence of

25   steps, except that in one alternative case ("case I") the adaptation is performed on the

center and surround areas of the opponent RFs, and not on the double-opponent RFs as in the color contrast case. Another difference vs the color contrast adaptation is that in the intensity contrast adaptation of case 1, an inverse transformation may not be applied. Intensity adaptation can be applied independently on achromatic images (non-color or black-and-white pictures) or on the intensity domain of color images. For intensity adaptation, the method emulates two types of ganglion cells of the magno pathway, the on-center and off M-opponent cells. In a preferred embodiment of the intensity adaptation, the remote adaptation is applied to the center sub-region of opponent RFs (or alternatively to the center and surround sub-regions of the opponent RFs), unlike in color contrast, in which remote adaptation is applied to double-opponent RFs. Alternatively, achromatic contrast adjustment can be performed on double-opponent RFs too.

The information contained in a color or black-and-white scene is processed through rod cells 10 (FIG. 1) or through the three cone types. In the first stage in the "achromatic contrast" or intensity adaptation method (algorithm), an emulation of this action is done under the assumption that the three cone types absorb the same amount of light. Alternatively, the starting point of the forward transformation in this case, as in the color contrast case, can be an image acquired using any of the means described above. Regardless of the color scale in which the image is obtained - RGB, XYZ, (Yxy), Lab, or any other CIE scale - the intensity value at each pixel can be obtained by known mathematical manipulations. Thus, the starting point is a known intensity value at each pixel.

The steps in the intensity adjustment method start in a similar fashion with that in the color contrast adjustment method, with the distinctive difference that one emulates rod cells and not cones. Thus, if the input is the intensity spectrum of a scene, an emulated pigment response $Y_{pigment}$ is given by

$$Y_{pigment} = \int_{visual\ range} I_{rod}(\lambda)\Re(\lambda)I(\lambda)d\lambda \qquad (17)$$

where $I_{rod}(\lambda)$ is the spectral absorption function of the rods as a function of the wavelength λ; $\Re(\lambda)$ is the reflectance property of the surface at any specific location in the image; and $I(\lambda)$ is the spectral composition of the illumination falling on this location.

5   In a similar fashion, the emulated responses of the rod-types at each pixel (or the intensity value at each pixel) R_{rod} are expressed by a Naka-Rushton equation as a function of their inputs $Y_{pigment}$,

$$R_{rod} = \frac{Y_{pigment}^{n}}{Y_{pigment}^{n} + \sigma_{(NR)}^{n}} \qquad (18)$$

Here too, in the case that the intensity information is extracted from rods, parameters n and σ_{NR} are similar to those related to cones (see eq. 2). Alternatively, eqs. 17 and

10   18 are not relevant and are not used if the starting point is an existing image.

Continuing along the lines of the color contrast equations, a "center" response before the adaptation is now defined as

$$G_{cen} = \int\int_{center\ area} R_{rod} f_{c}(x,y)dxdy \qquad (19)$$

where the RF region is preferably circular, f_c is preferably a Gaussian decaying spatial-weight function. analogous to that in eq. 4. The "surround" response, which

15   now represents the surround sub-region of the RF of an M-RGC, is defined as

$$G_{srnd} = \iint\limits_{surround\ area} R_{rod} f_s(x, y)dxdy \qquad (20)$$

where f_s is also a Gaussian spatial-weight function with asign opposite to that of f_c. As in the color contrast case, the total weight of f_c is 1, while the total weight of f_s is 1/CSR. The steps above are repeated for off-center type cells.

As mentioned already, a key difference in intensity contrast vs. the color contrast adaptation is that in the present invention a "remote" component needed for the intensity adaptation is computed already at the opponent RF stage for both "center" and "surround" regions of the on-and off-center RFs. The "remote" signal (or "response") representing an adaptation component derived from peripheral regions, i.e., areas that extend outside and beyond the classical RF ("remote adaptation"), is calculated separately for each of the sub-regions (or alternatively applied only to the "center" area of the on-center and off-center cell types) using an equation of the type:

$$G_{remote} = \iint\limits_{remote\ area} G *_{cen} f_r(x, y)dxdy \qquad (21)$$

where $G*_{cen}$ is a filtered response (with a definition similar to that in the color contrast case) similar to the center response in eq. 19, but related here to the remote area through the convolution with a remote spatial weight function f_r. Alternatively, an additional remote signal can be built with a surround filtered response $G*_{srnd}$ similar to the surround response of eq. (20), but related here to the remote area (by convolution with a remote spatial weight function f_r, and using an integration similar to that in eq. 21).

The mechanism for the intensity adaptation application can now be calculated in one of two ways. One way (Case 1) is to apply the adaptation and the remote area

influence at the emulation stage of ganglion RF regions (eqs. 20, 21) or alternatively (Case 2) at the stage of the cortical level, in which case the adaptation is applied on the double-opponent RFs (similar to the color coded cells case).

Case 1:_ The M-RGCs 'center' and 'surround' sub-regions are adapted

5   separately (the values of the parameters are based on electrophysiological findings, in a similar manner to that found and analyzed for M-RGCs by Shapley & Enroth-Cugell and Dahari & Spitzer). As described in these references, and as for color contrast, the response of an "on" and "off" M-RGC to a stable visual stimulus at t=∞ (the "static case") is:

$$R_{op}\left(t = \infty\right) = \frac{G_{cen}}{G_{cen} + \sigma_{cen}} - \frac{G_{srnd}}{G_{srnd} + \sigma_{srnd}} \qquad (22)$$

10   Where σ is an adaptation factor which depends on the stimulation (here, at t=∞) of both the sub-regions and that of the remote area. In other words, the adapted opponent response is obtained by a subtraction of the adapted surround response from the adapted center response. The adaptation factor of each sub-region has separate 'local' and 'remote' components and consists of the same spectral properties as the sub-

15   region. For example, for the "center" sub-region, the adaptation factor is given by:

$$\sigma_{cen} = \sigma_{cen,local} + \sigma_{cen,remote} \qquad (23)$$

$$where \quad \sigma_{cen,local} = \alpha_{cen}G_{cen} + \beta_{cen}$$

$$and \quad \sigma_{cen,remote} = c_{cen}G_{remote}$$

The adaptation factors for surround sub-regions are similarly defined, and include both local and remote adaptation components. α, β and c for both center and surround adaptation factors are constants with different values for the 'center' and for the 'surround'. α and β are determined as in Dahari and Spitzer, while c in eq. 23, the

weight function of the remote adaptation component, typically ranges between 1-30 for both center and surround adaptation factors. The method can be alternatively applied without the surround signal and its remote mechanisms, i.e. using only the first term in eq. 22. Furthermore, the method can be alternatively applied without

5 considering the local adaptation, i.e. using only the second term in eq. 23.

If one defines a= α +1 and b=β and substitutes the terms of eq. 23 in eq. 22, the emulated responses of the on-center and off-center cells M-RGC are written as:

$$R_{op} = \frac{G_{cen}}{a_{cen}G_{cen} + b_{cen} + c_{cen}G_{remote}} - \frac{G_{srnd}}{a_{srnd}G_{srnd} + b_{srnd} + c_{srnd}G_{remote}} \tag{24}$$

For the dynamical case, one can follow a similar sequence to that expressed

10 by eqs. 9-11, to be used here however for achromatic intensity.

Case 2: In the alternative embodiment of performing the adaptation for intensity contrast by applying it at the double-opponent stage, eqs. 22-24 are not implemented. In general, the steps of the method for intensity adaptation at the double-opponent stage follow those of the color contrast adaptation. One difference

15 vs. the color contrast case is that the input of the do-surround sub-region is optional, and intensity adaptation can be performed without it. In analogy with eq. 1, the opponent cell's response, R_{op} is the subtraction between the center and the surround output function values of on-center and off-center cell types:

$$R_{op} = G_{cen} - G_{srnd} \tag{25}$$

where G_{cen} is equivalent to G_c and G_{srnd} is equivalent to G_s, both however being applied here for the cells that code the intensity domain. The off- center cells have similar RF structure but with opposite signs.

In analogy with the color contrast case, the achromatic double-opponent center

5   signal (do-center response) is built from the filtered responses of the opponent on- and off-center cells:

$$G_{(do-c)} = \iint\limits_{center\ area} R^*_{on} f_{(do-c)}(x,y)\,dx\,dy \tag{26}$$

where R^*_{op} is a filtered response similar to R_{op} but related to a different area (as explained in the color contrast case), an area defined in the integration. The typical size of the do-center contains 1-16 pixels in the simulations applications.

10   The ' do-surround' signal is similarly defined as

$$G_{(do-s)} = \iint\limits_{surround\_area} R^*_{on} f_{(do-s)}(x,y)\,dx\,dy \tag{27}$$

The do-remote signal, in analogy with eq. 4 is given by

$$G_{(do-remote)} = \iint\limits_{remote\ area} R^*_{(do-c)} f_r(x,y)\,dx\,dy \tag{28}$$

The double-opponent responses (the responses of the on-center and off-center double-opponent M-RGCs), before the adaptation stage, are given by:

$$R_{do} = G_{(do - c)} - G_{(do - s)} \qquad (29)$$

The do-remote signal can alternatively be built from the filtered response R^*_{do} of the double-opponent RF. The adaptation, for still and video images, as well as the inverse transformation are then performed analogously to those in the color contrast case, following the same sequence of steps, except for the fact that it refers here to achromatic information, and that, as mentioned above, the intensity adaptation can be performed without the input of the do-surround response.

All publications, patents and patent applications mentioned in this specification are herein incorporated in their entirety by reference into the specification, to the same extent as if each individual publication, patent or patent application was specifically and individually indicated to be incorporated herein by reference. In addition, citation or identification of any reference in this application shall not be construed as an admission that such reference is available as prior art to the present invention.

While the invention has been described with respect to a limited number of embodiments, it will be appreciated that many variations, modifications and other applications of the invention may be made.